

Electrical Power Engineering (2)

Code: EP2207

Lecture: 4

Tutorial: 4

Total: 8

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Network Equations and Solution

Node Equations

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} y_{11} & -y_{12} & -y_{13} \\ -y_{21} & y_{22} & -y_{23} \\ -y_{31} & -y_{32} & y_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

$$\mathbf{I} = \mathbf{y}_{\text{Bus}} \mathbf{V}$$

$$\mathbf{V} = \mathbf{y}_{\text{Bus}}^{-1} \mathbf{I}$$

$$\mathbf{V} = \mathbf{Z}_{\text{Bus}} \mathbf{I}$$

Network Equations and Solution

Node Equations

Y_{Bus} is the admittance matrix:

- ▶ It is a square matrix
 - ▶ The main diagonal contains the self-admittance: the summation of all admittances connected to this node
 - ▶ The off diagonal contains the mutual admittances between the different nodes
 - ▶ The main diagonal contains admittances with positive signs, which means a negative value (the admittance itself has a negative value, i.e. $-j x$)
 - ▶ The elements in the off diagonal are admittances with negative signs, which means positive values.
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Network Equations and Solution

Node Elimination

Nodes are classified into main nodes and auxiliary nodes

Insignificant nodes are eliminated and the significant ones are maintained

Suppose that we have some main nodes denoted by "K" and the auxiliary nodes denoted by "M"

Set the associated current components to zero

$$\begin{bmatrix} I_A \\ 0 \end{bmatrix} = \begin{bmatrix} K & L \\ L^T & M \end{bmatrix} \begin{bmatrix} V_A \\ V_x \end{bmatrix}$$

Network Equations and Solution

Node Elimination

$$\begin{bmatrix} I_A \\ 0 \end{bmatrix} = \begin{bmatrix} K & L \\ L^T & M \end{bmatrix} \begin{bmatrix} V_A \\ V_x \end{bmatrix}$$

$$I_A = K V_A + L V_x$$

$$0 = L^T V_A + M V_x$$

$$V_x = -M^{-1} L^T V_A$$

$$I_A = K V_A - L M^{-1} L^T V_A$$

$$I_A = [K - L M^{-1} L^T] V_A$$

$$I_A = y_{\text{Bus-new}} V_A$$

$$y_{\text{Bus-new}} = K - L M^{-1} L^T$$

Network Equations and Solution

Example: A small power system has the following bus admittance matrix.

$$\begin{bmatrix} -j9.8 & 0.0 & j4.0 & j5.0 \\ 0.0 & -j8.3 & j2.5 & j5.0 \\ \hline j4.0 & j2.5 & -j14.5 & j8.0 \\ j5.0 & j5.0 & j8.0 & -j18.0 \end{bmatrix}$$

Use matrix elimination technique to eliminate nodes 3 and 4. Draw the equivalent circuit of the reduced network.

Network Equations and Solution

$$\mathbf{Y}_{\text{bus}} = \begin{bmatrix} \mathbf{K} & \mathbf{L} \\ \mathbf{L}^T & \mathbf{M} \end{bmatrix} = \left[\begin{array}{cc|cc} -j9.8 & 0.0 & j4.0 & j5.0 \\ 0.0 & -j8.3 & j2.5 & j5.0 \\ \hline j4.0 & j2.5 & -j14.5 & j8.0 \\ j5.0 & j5.0 & j8.0 & -j18.0 \end{array} \right]$$

The inverse of the submatrix in the lower right position is

$$\mathbf{M}^{-1} = \frac{1}{-197} \begin{bmatrix} -j18.0 & -j8.0 \\ -j8.0 & -j14.5 \end{bmatrix} = \begin{bmatrix} j0.0914 & j0.0406 \\ j0.0406 & j0.0736 \end{bmatrix}$$

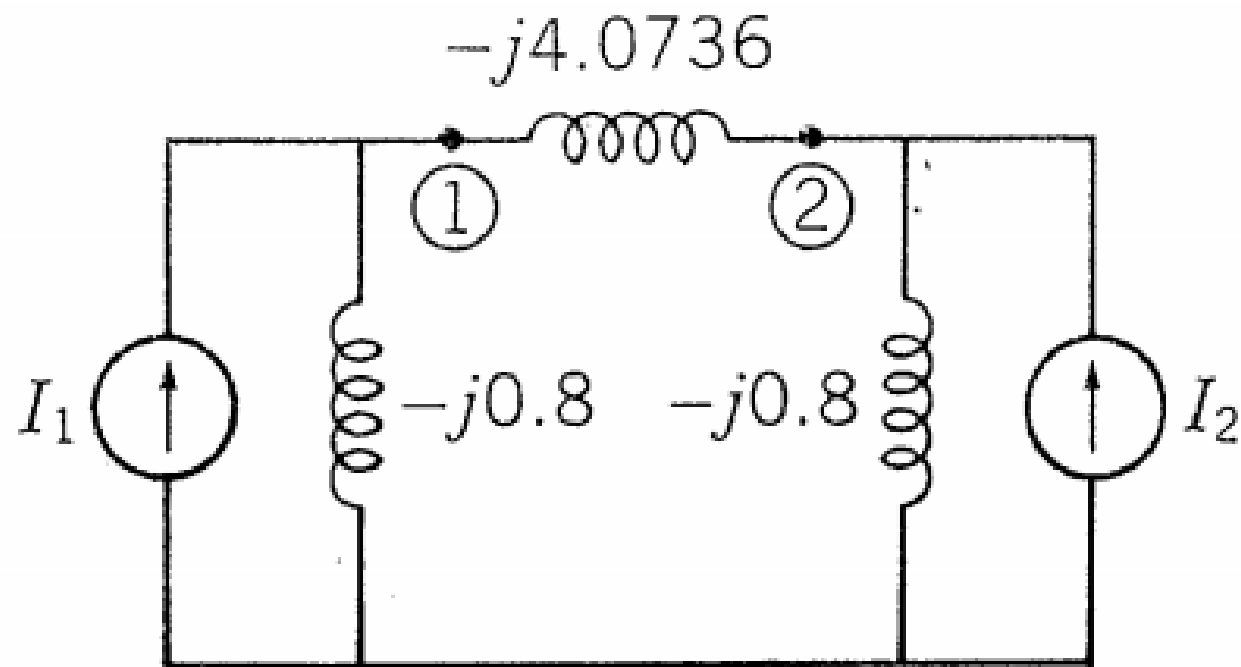
Then

$$\begin{aligned} \mathbf{LM}^{-1}\mathbf{L}^T &= \begin{bmatrix} j4.0 & j5.0 \\ j2.5 & j5.0 \end{bmatrix} \begin{bmatrix} j0.0914 & j0.0406 \\ j0.0406 & j0.0736 \end{bmatrix} \begin{bmatrix} j4.0 & j2.5 \\ j5.0 & j5.0 \end{bmatrix} \\ &= - \begin{bmatrix} j4.9264 & j4.0736 \\ j4.0736 & j3.4264 \end{bmatrix} \end{aligned}$$

Network Equations and Solution

$$\mathbf{Y}_{\text{bus}} = \mathbf{K} - \mathbf{LM}^{-1}\mathbf{L}^T = \begin{bmatrix} -j9.8 & 0.0 \\ 0.0 & -j8.3 \end{bmatrix} - \mathbf{LM}^{-1}\mathbf{L}^T$$

$$\mathbf{Y}_{\text{bus}} = \begin{bmatrix} -j4.8736 & j4.0736 \\ j4.0736 & -j4.8736 \end{bmatrix}$$



CONTROL OF VOLTAGE AND REACTIVE POWER

Reactive Power Control

The balance of reactive power is achieved when the generated reactive power by synchronous machines and capacitances is equal to the reactive power of the loads plus the reactive transmission losses

Imbalance in active power causes frequency fluctuations

Imbalance in reactive power causes a deviation of the voltages from the desired values

CONTROL OF VOLTAGE AND REACTIVE POWER

The voltage drops on the lines are normally small

The voltages of different nodes are almost the same and the voltage drop can be neglected

The voltage is controlled by controlling the reactive power

Increasing the reactive power increases the voltage, while increasing the consumed reactive power decrease the voltage

CONTROL OF VOLTAGE AND REACTIVE POWER

The reactive power cannot be transported over long distances in the system, since normally $X \gg R$

Important sources of reactive power are

- Overexcited synchronous machines
 - Capacitor banks
 - The capacitance of overhead lines and cables
-

CONTROL OF VOLTAGE AND REACTIVE POWER

The main consumers of reactive power are:

- Under-excited synchronous machines
 - Inductive static loads
 - Induction motors
 - Shunt reactors
 - The inductance of overhead lines and cables
 - Transformer inductances
 - Line commutated static converters
-

CONTROL OF VOLTAGE AND REACTIVE POWER

Switching of shunt capacitors and reactors can control the reactive power

If thyristors are used to switch capacitors and/or to control the current through shunt reactors, a fast and step-less control of the reactive power is obtained

Such a device is called SVC (Static Var Compensator)

CONTROL OF VOLTAGE AND REACTIVE POWER

Voltage Control

Factors affecting the selection of power system voltage

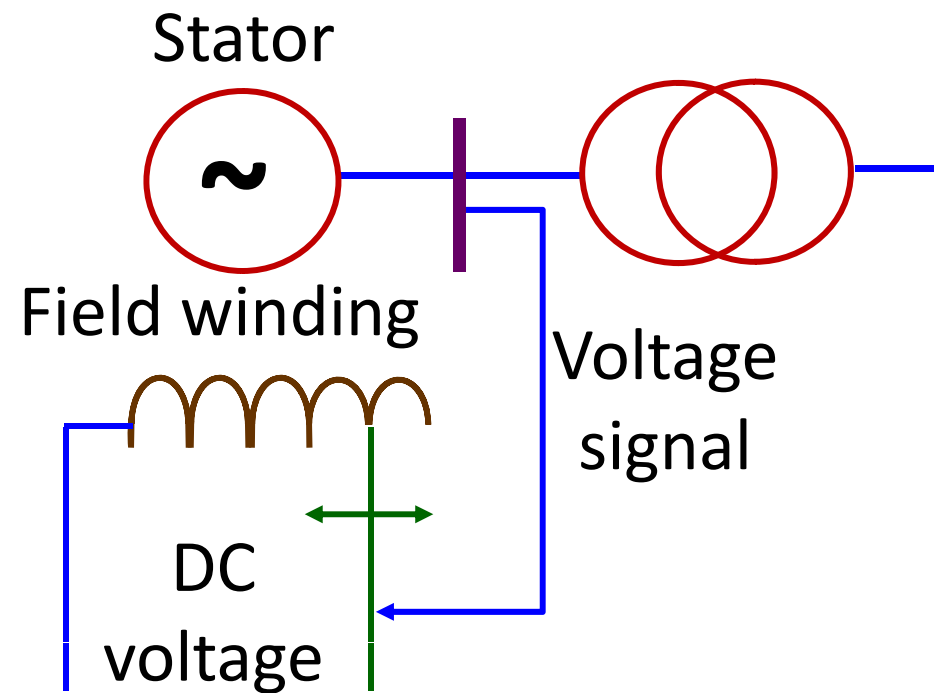
- Terminal voltages of synchronous machines
 - Transmitted reactive power
 - Impedances of lines
 - Turns ratio of transformers
-

CONTROL OF VOLTAGE AND REACTIVE POWER

The generator voltage can be maintained constant by using an Automatic Voltage Regulator (AVR)

The AVR controls the excitation of the machine so that the voltage is kept constant at the set value

This method cannot easily be used for a single generator when a number of generators run in parallel



CONTROL OF VOLTAGE AND REACTIVE POWER

Large reactive transmissions cause large voltage drops, therefore, they should be avoided

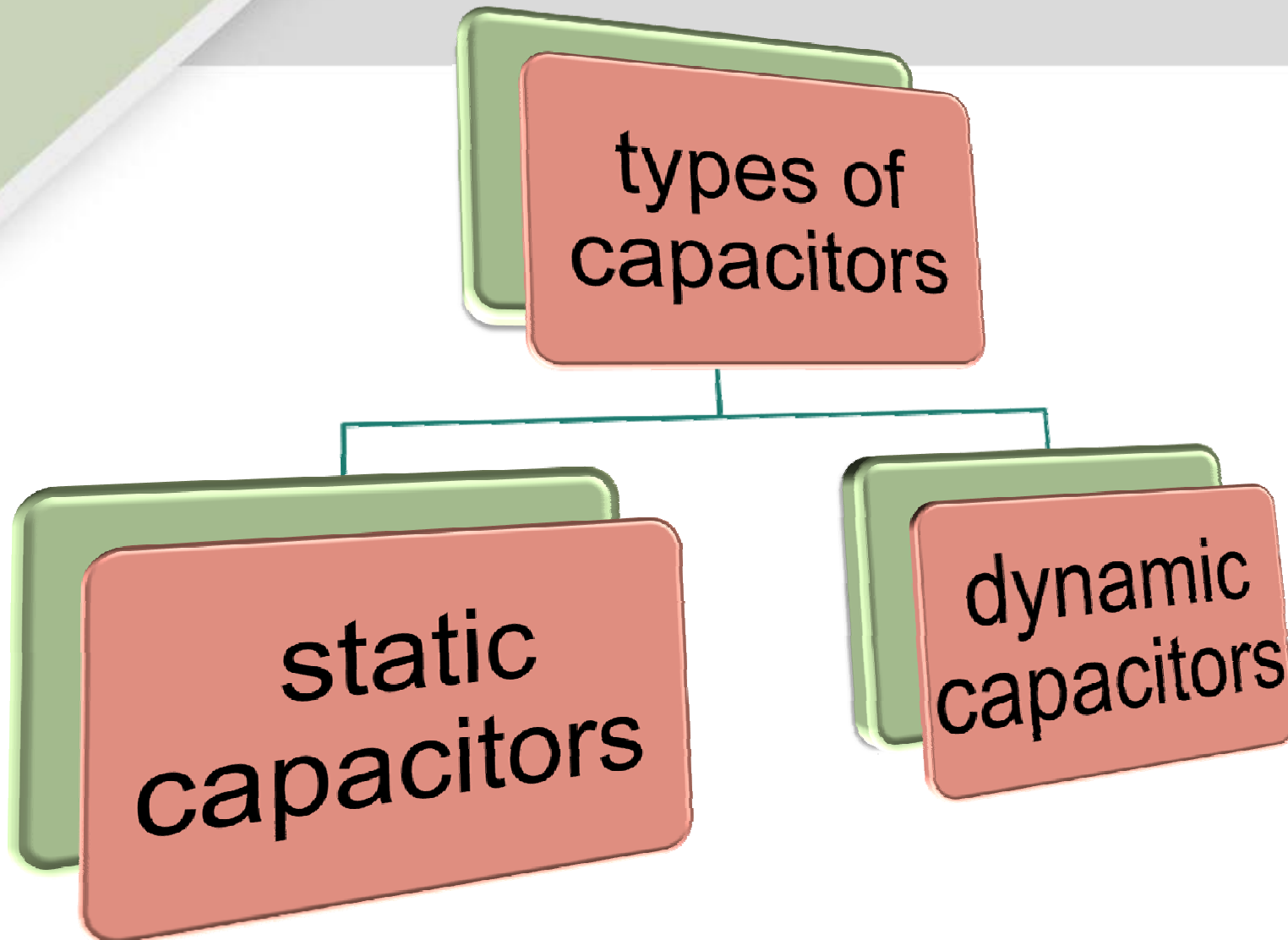
The production of reactive power should be as close as possible to the reactive loads

The most cost-effective way is to use shunt capacitors which are switched according to the load variations

A SVC can be economically motivated if fast response or accuracy in the regulation is required

Shunt reactors must sometimes be installed to limit the voltages to reasonable levels

CONTROL OF VOLTAGE AND REACTIVE POWER



CONTROL OF VOLTAGE AND REACTIVE POWER

dynamic capacitors "synchronous generators"

Synchronous compensators are installed for voltage control

These are synchronous machines without turbine or mechanical load, which can produce and consume reactive power by controlling the excitation

New installations of synchronous compensators are very rare

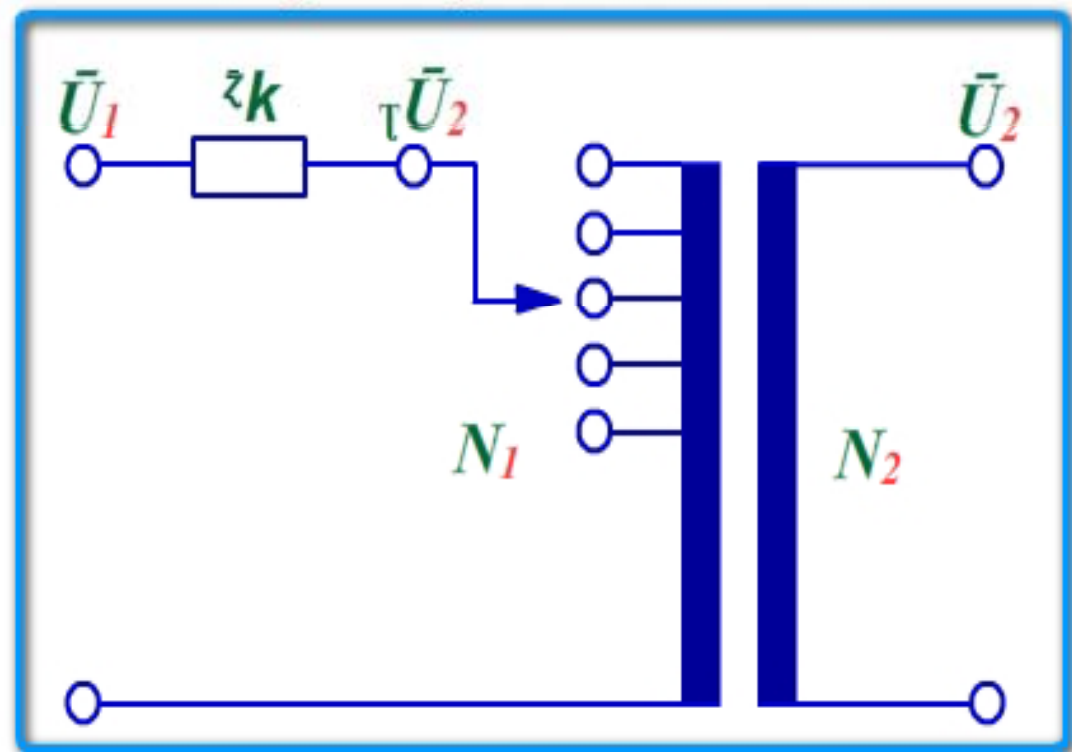
Instead, capacitors are used at the receiving end of the transmission line to vary the amount of the reactive power

CONTROL OF VOLTAGE AND REACTIVE POWER

Tap- changing transformer

The turns ratio of a transformer is changed to control the voltage in power systems

Certain transformers are equipped with a number of taps on the high voltage side. Voltage control can be obtained by switching between these taps.



CONTROL OF VOLTAGE AND REACTIVE POWER

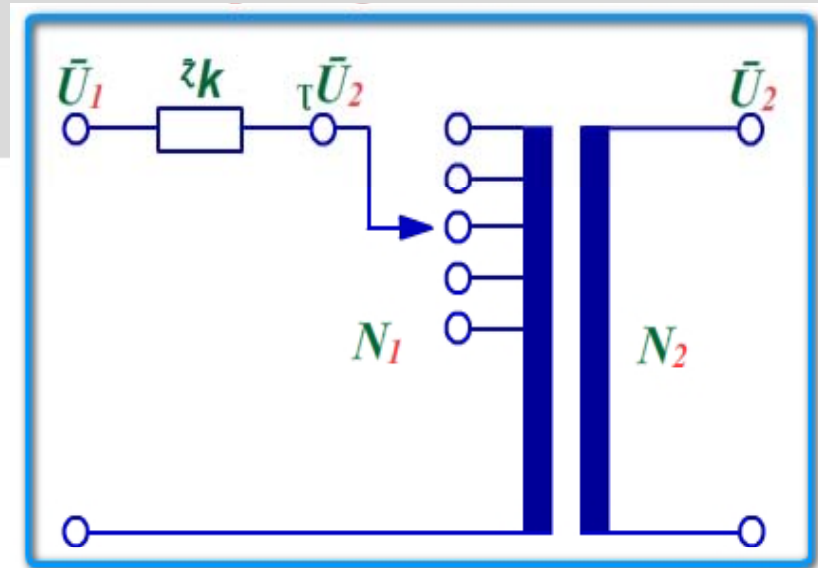
Tap- changing transformer

The switching can be done online during operation

Normally the taps are placed on the high voltage winding, the upper side

The lowest current needs to be switched

The number of turns in the high voltage side is larger, which gives better regulation of the variation ratio



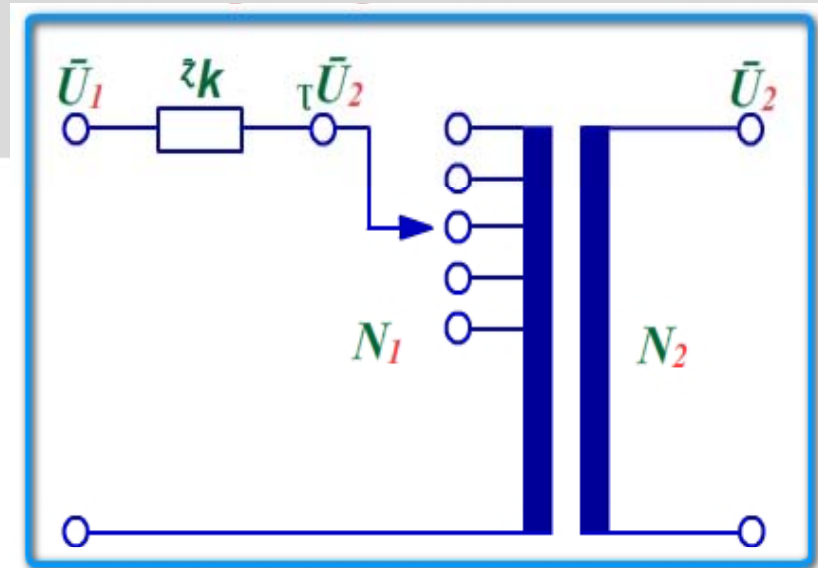
CONTROL OF VOLTAGE AND REACTIVE POWER

Tap- changing transformer

Sometimes, the turns ratio cannot be changed during operation, but when the transformer is off load

In this case, the voltage level can only be changed in general but the voltage variations in the network are not controlled

The windings used for tap setting are about 10% of the total windings of the transformer

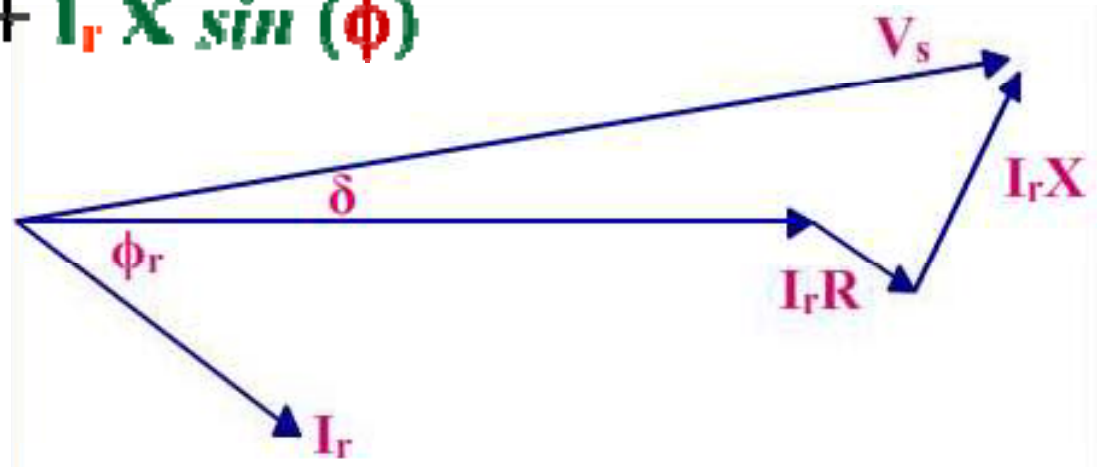


CONTROL OF VOLTAGE AND REACTIVE POWER

Improving the regulation

$$\Delta V = I_r R \cos(\phi) + I_r X \sin(\phi)$$

$$\Delta V = \frac{PR + QX}{V_r}$$



$$Reg\% = \frac{\Delta V}{V_r} * 100 = \frac{I_r R \cos(\phi) + I_r X \sin(\phi)}{V_r} * 100$$

$$\Delta V = \frac{PR + QX}{V_r^2} * 100 = \frac{P_r}{V_r^2} [R + X \tan(\phi_r)]$$

CONTROL OF VOLTAGE AND REACTIVE POWER

$$\Delta V = \frac{P_r}{V_r^2} [R + x \tan(\phi_r)]$$

To reduce the voltage regulation

Increase the operating voltage

Improve the power factor at the receiving end

Reduce the resistance of the transmission line,
e.g. using double circuit

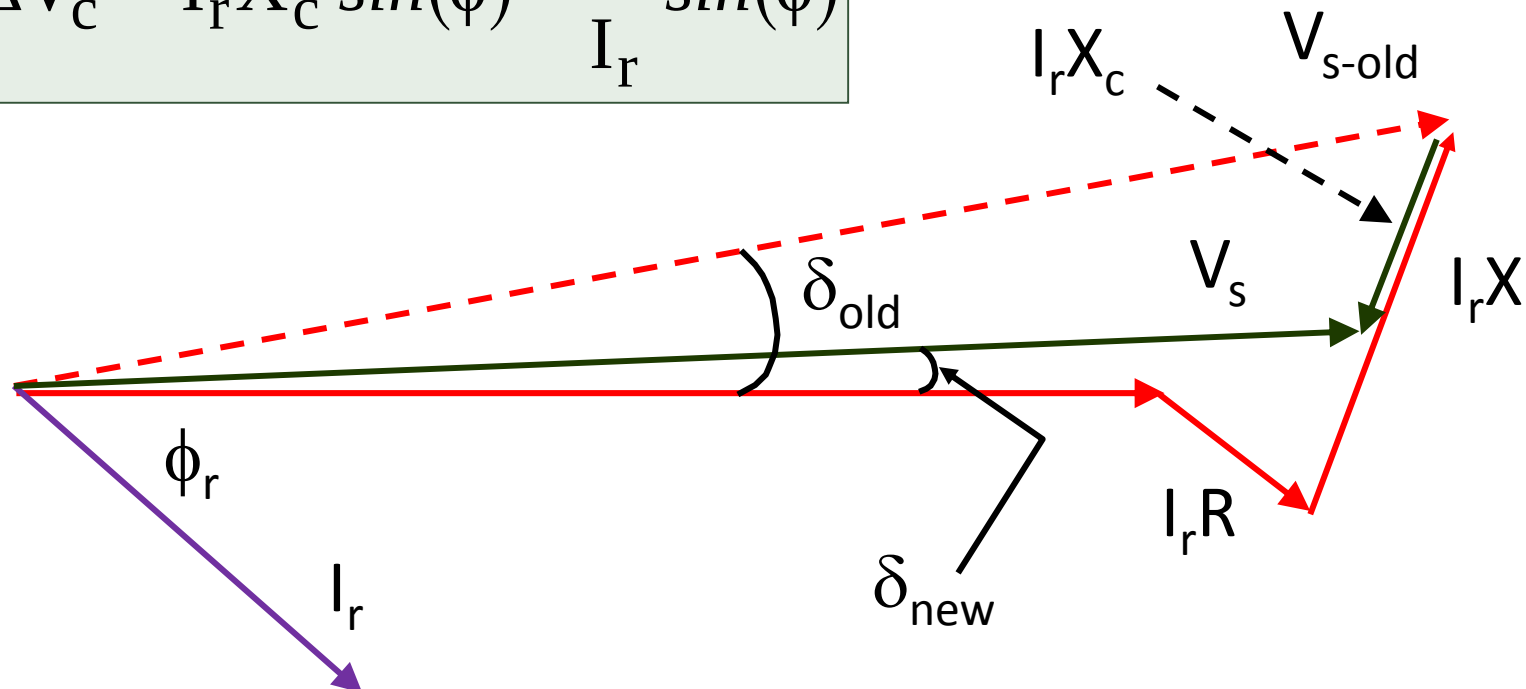
Reduce the reactance of TL, e.g. using double circuit,
using bundle conductors or using series capacitors

CONTROL OF VOLTAGE AND REACTIVE POWER

With a capacitor used at the receiving end

$$\Delta V = I_r R \cos(\phi) + I_r X \sin(\phi) - I_r X_c \sin(\phi)$$

$$\Delta V_c = I_r X_c \sin(\phi) = \frac{Q}{I_r} \sin(\phi)$$



CONTROL OF VOLTAGE AND REACTIVE POWER

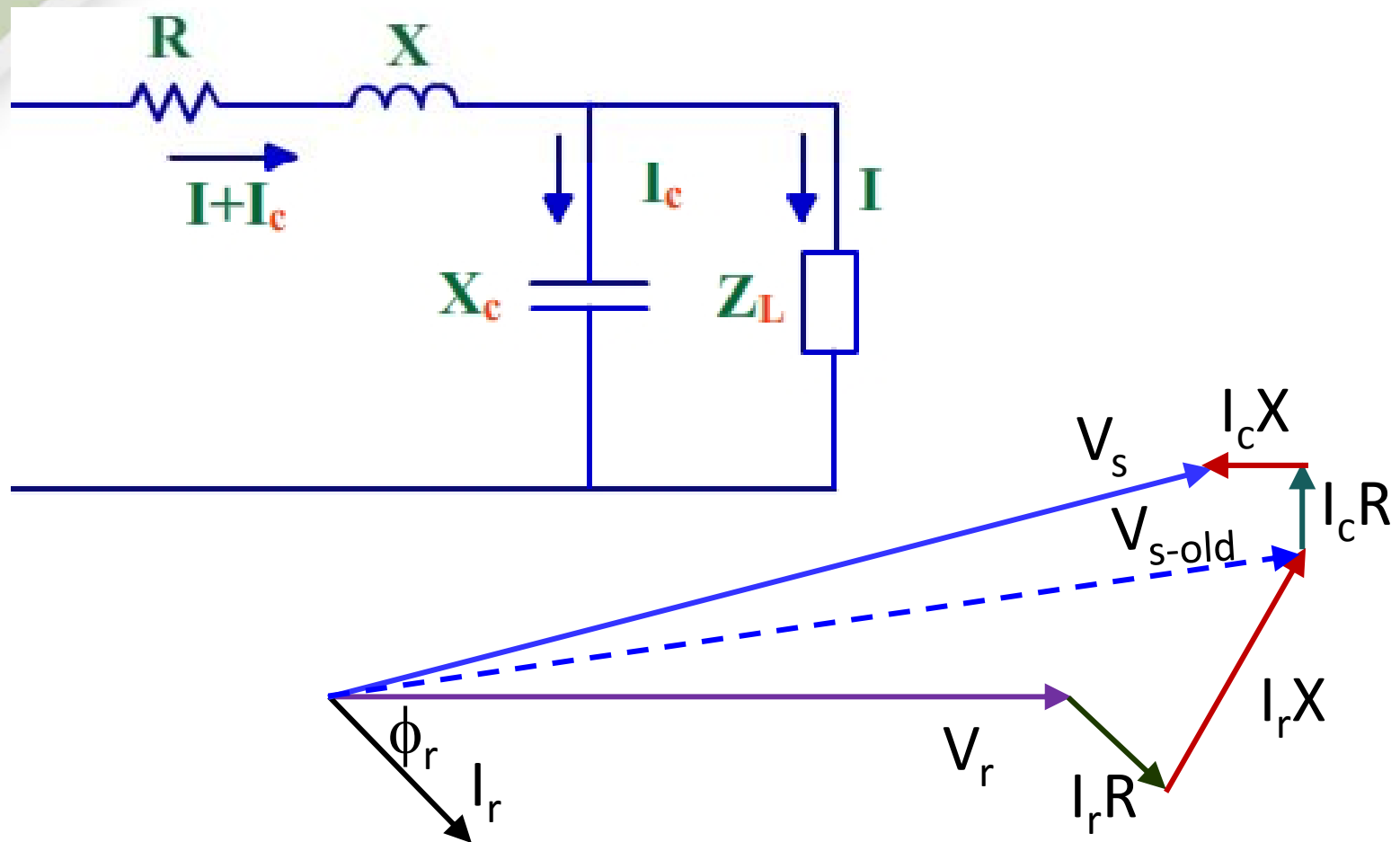
Disadvantages of low power factor

- Higher copper losses
- Poor voltage regulation
- Greater conductor size
- Larger apparent power rating of equipments
- Reduced handling capacity of the system

To improve the power factor, parallel or series capacitors are connected

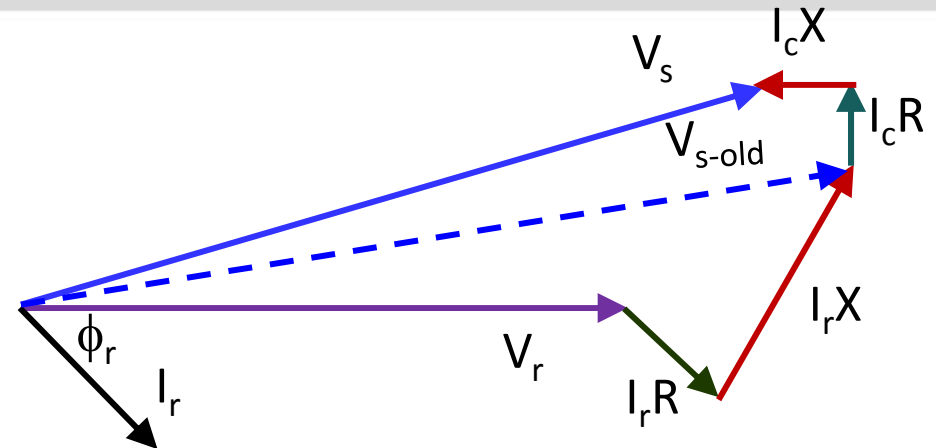
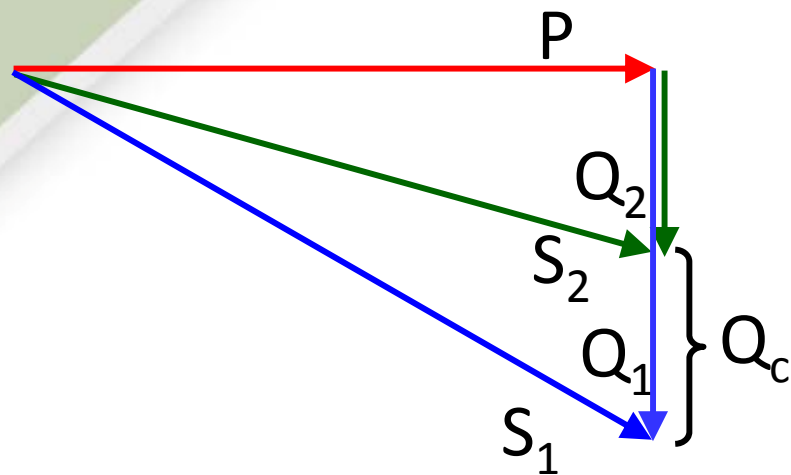
CONTROL OF VOLTAGE AND REACTIVE POWER

Parallel capacitors



CONTROL OF VOLTAGE AND REACTIVE POWER

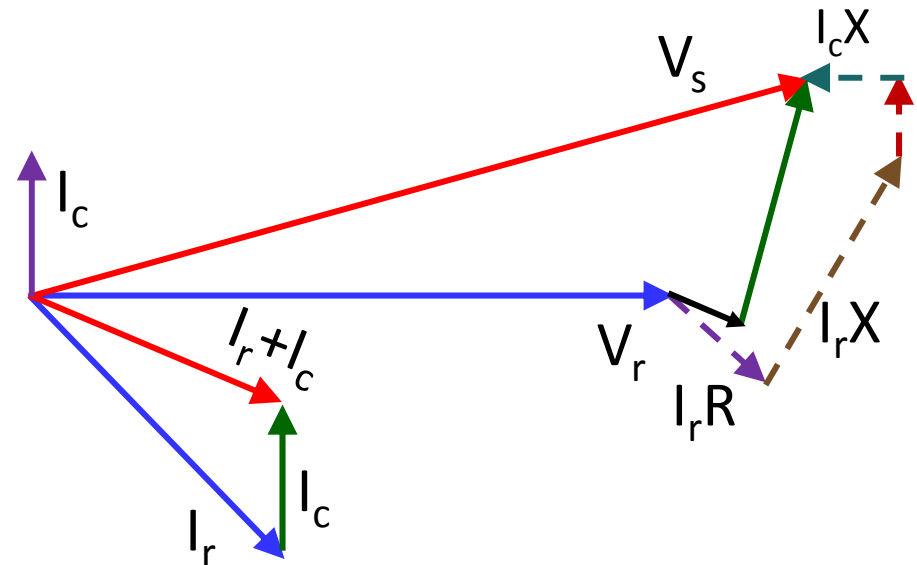
Parallel capacitors



$$\Delta V = I_r R \cos(\phi) + I_r X \sin(\phi) - I_c X$$

$$\Delta V'_c = I_c X = \frac{V_r}{X_c} X$$

$$\Delta V'_c = \frac{Q'}{V_r} X$$

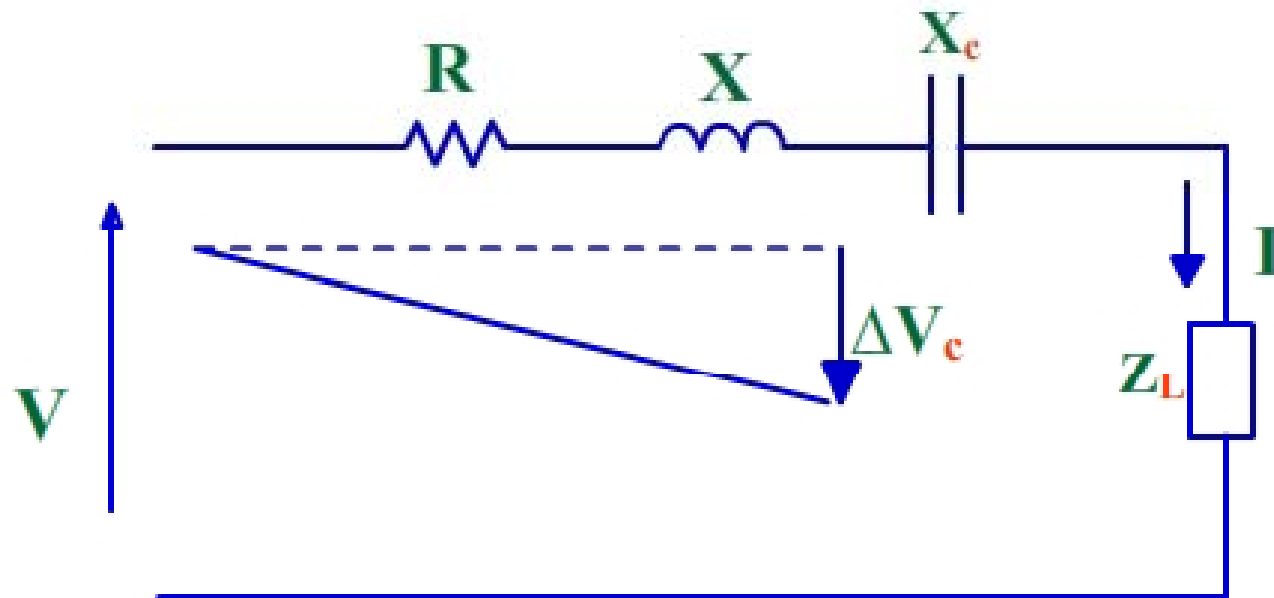


CONTROL OF VOLTAGE AND REACTIVE POWER

Comparison between series and shunt capacitors

In the case of series compensation

$$\Delta V_{c-s} = \frac{Q}{I} \sin(\phi)$$



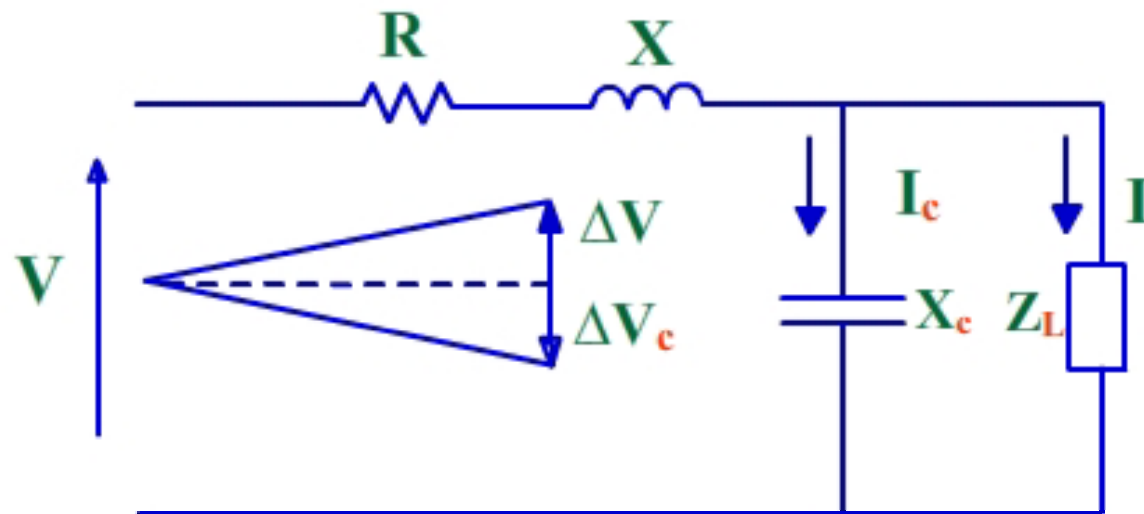
CONTROL OF VOLTAGE AND REACTIVE POWER

Comparison between series and shunt capacitors

Parallel capacitor compensation

In the case of parallel compensation

$$\Delta V_{c-p} = \frac{Q'}{V_r} X$$



CONTROL OF VOLTAGE AND REACTIVE POWER

Comparison between series and shunt capacitors

Parallel comparison

- Gradual increase of the voltage
- Capacitor is placed on the ground level
- Failure of capacitor causes a voltage reduction

Series comparison

- Sudden increase in the voltage at the capacitor location
- Capacitor has to be placed in on the tower
- Failure of the capacitor causes a line break

CONTROL OF VOLTAGE AND REACTIVE POWER

Comparison between series and shunt capacitors

Parallel comparison

- The capacitor current is a part of load current

$$\Delta V_{c-p} = \frac{Q'}{V_r} X$$

Series comparison

- The capacitor current is the load current

$$\Delta V_{c-s} = \frac{Q}{I} \sin(\phi)$$

CONTROL OF VOLTAGE AND REACTIVE POWER

Comparison between series and shunt capacitors

The ratio between the reactive power obtained from the two capacitors for the same voltage change:

$$\frac{Q'}{V_r} \approx \frac{Q}{I} \sin(\phi)$$
$$\frac{Q'}{Q} = \frac{V_r}{IX} \sin(\phi) \approx \frac{V_r * 0.6}{0.1 V_r} \approx 6$$

The reactive power required from the parallel capacitor is equivalent to about six series capacitors

Parallel capacitor is more expensive than series one